US-BLM, Colorado
Acid Mine Drainage – American Tunnel Mine

EC Treatment Reactor Testing and Results Report

Prepared by:
Waste Water Management, Inc.
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Electrochemical Treatment Testing and Results Report

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EXECUTIVE SUMMARY

Background

Water quality in the Animas River near Silverton, Colorado is currently impacted by contaminated groundwater draining from former mining operations in the surrounding watershed. In May 2012 the U.S. Bureau of Land Management (BLM) in coordination with the Animas River Stakeholders Group issued a Request for Proposals from qualified contractors to perform an "Electrochemical Water Treatment Pilot Test" on acid mine drainage water from the American Tunnel adit in Gladstone, Colorado. On July 23, 2012 the BLM awarded the contract to Waste Water Management, Inc. (WWMI) of Fairfax, Virginia.

Field Sampling and Testing

In September 2012 WWMI engineers mobilized to Gladstone, Colorado and initiated 20 gallon per minute continuous flow electrochemical reactor tests on the water flowing from the abandoned American Tunnel mine. Due to difficulties experienced with low pH and high conductivity water the continuous flow tests were ceased after two days. Immediately thereafter batch reactor tests were set up and run for the following three days with all water samples delivered to the Greene Analytical Laboratories in Durango, Colorado after which time all initial field work was deemed complete.

In August 2013 WWMI engineers returned to the site with larger power generation and current converter equipment and again initiated 20 gallon per minute continuous flow testing. Similar to the results of the 2012 trials the 2013 work utilizing the larger power components also proved to be ineffective due to the low pH and the high conductivity water. So as to be

productive and be in a position to draw reasonable conclusions, on the third day of testing the WWMI engineers designed and fabricated a smaller electrochemical reactor and applied a flow rate ranging between 0.4 and 1.0 gallon per minute. The water samples taken during the final two days of testing were also delivered to the Greene Analytical Laboratories and the analytical results were greatly improved from the 2012 tests.

Results and Conclusions

In all water samples taken from the American Tunnel mine adit, the pH was measured in the range of 4.2 to 5.3 and the conductivity ranged between 2000 and 2400. Also measured in all samples were iron, aluminum sulfates and trace levels of several heavy metals. In both testing programs the samples were analyzed for general chemistry components including alkalinity, chloride, conductivity, pH, phosphate, sulfate, and total dissolved solids. In addition, samples of treated water were analyzed for dissolved and total recoverable constituents including aluminum, iron, silica, silicon, calcium, magnesium, potassium, sodium, cadmium, copper, lead, manganese, zinc, and mercury.

Observations of the results of all analyses and in particular the continuous flow using the small reactor indicated several facts about the potential use of electrochemical technology for the treatment of mine drainage water as follows.

- The rapid formation of iron floc was observed in each test with the floc settling completely within 15 minutes leaving a clear supernatant.
- The reduction in dissolved iron was inversely proportional with an increase in hydraulic retention time in the reactor.
- Dissolved aluminum (from the aluminum electrodes) was increased by a factor of 10.
- Sodium was essentially unchanged
- The reduction of both dissolved and recoverable cadmium was approximately 30%
- The reduction of both dissolved and recoverable copper was approximately 50%
- The reduction of both dissolved and recoverable lead was at least 50%

Due to the difficulties encountered with the low pH high and conductivity water which hampered the larger scale continuous testing it was impossible to accurately predict the operating costs of a full scale electrochemical system without further testing. It is postulated that a pretreatment system for the chemical adjustment of the pH into a neutral range would be beneficial to an electrochemical system for treatment of mine drainage water.

1.0 INTRODUCTION

Water quality in the Animas River in San Juan County, Colorado is currently impacted by contaminated groundwater draining from former mining operations in the surrounding watershed. The groundwater flows to the surface at several adits and follows surface contours until it reaches existing streams, which flow to the Animas River. The U.S. Bureau of Land Management (BLM) is working with the Animas River Stakeholders Group (ASRG) to investigate water treatment technologies for potential use in improving the water quality in the Animas River near Silverton, Colorado by treating the adit discharge water before it reaches existing streams. On May 30, 2012 the BLM issued a Request for Proposals (RFP) from qualified contractors to perform an "Electrochemical Water Treatment Pilot Test" on acid mine drainage water from the American Tunnel adit in Gladstone, Colorado. On July 23, 2012 the BLM awarded the contract to Waste Water Management, Inc. (WWMI) of Fairfax, Virginia.

1.1 Scope of Work

The American Tunnel adit is located north of Silverton, Colorado in the old mining town of Gladstone. Groundwater from the adit discharges into a larger stream known as Upper Cement Creek which then discharges into the Animas River.

Early investigations of the adit drainage water chemistry showed high levels of iron and other metals such as aluminum, manganese, and zinc, as well as lower concentrations of the heavy metals copper, cadmium, and lead. The pH of the water ranged from 4.2 to 5.3.

The scope of WWMI's pilot testing efforts was delineated in the BLM issued Statement of Work RFP dated May 18, 2012 which listed the following objectives, tasks and deliverables for the electrochemical treatment pilot test.

Objectives:

1. The primary objective of the BLM and its partners is to improve the quality of water in the Animas River and its tributaries in San Juan County, Colorado.
2. The objective of the pilot study is to evaluate the suitability and cost effectiveness of using an electrochemical process for the treatment of low pH mine drainage water.

Tasks:

1. Conduct a field pilot test of an electrochemical technology for the treatment of mining impacted drainage waters at the American Tunnel mine at Gladstone, Colorado; said pilot test to be performed during the months of August or September 2012.
2. Demonstrate the capability of the electrochemical technology to meet water quality treatment goals as defined in Appendix B of the Statement of Work.
3. Identify and characterize the input requirements and reagents, the power consumption and the byproduct waste streams of the electrochemical treatment technology.
4. Gather sufficient data in the pilot study necessary to extrapolate the design of a full scale water treatment system.
5. Recommend whether it is more advantageous and cost effective to treat the drainage water from each mine individually or collectively.
6. Provide estimates for the capital and operating costs of a full scale operation.
7. Provide an estimated characterization for the wastes produced by a full scale system.
8. Provide an opinion of potential cost savings if the water quality treatment goals were less stringent.
9. Provide an estimate of the number of operators required for a full scale system along with the required operation training.

Deliverables:

1. Prior to the pilot test, provide a Health and Safety Plan.
2. At the completion of the pilot test, provide a DRAFT written report that contains the following:
    a. A table showing analysis of the raw water and treated water as collected as part of the pilot test.
    b. Treatment goals used to design the pilot test.

c. Description of the pilot test performed including a process flow diagram.

d. Description of any difficulties encountered during the pilot test, and how they impact the ability to use the pilot test to estimate full-scale implementation.

e. Raw test data provided in a report appendix and a summary of treatment data in the report text.

f. Statement that data was collected to provide the contractor with the data required to scale up the pilot test system into a full-scale system.

g. Recommendation to treat each of the adits separately or to commingle into a single stream.

h. Recommendation for a full-scale system.

i. Estimate of capital cost for a full-scale system.

j. Estimate of annual operations and maintenance cost for a full-scale system.

k. Recommend the number of operators required to operate a full-scale system and the level of training required for these operators.

3. Provide a FINAL written report incorporating comments from the ARSG.

2.0 BACKGROUND OF THE EC PROCESS AND TECHNOLOGY

The *Rigby EC Process* is an electrochemical oxidation technology which was developed to be a departure from conventional biological and chemical wastewater treatment technologies. To date it has been proven to be effective in the treatment of a variety of municipal and industrial wastewater streams for removal of biochemical oxygen demand, heavy metals, oil & grease, suspended solids, and complex organic constituents. However, until now the *Rigby EC Process* had never been tested on wastewater streams polluted from mining activities.

Electrochemical treatment is a well-known process generally involving the application of electrical energy to a liquid via an electrolytic cell, which consists of a reactor containing the liquid and pairs of anode and cathodes connected to a power supply. Electrolysis of water occurs within the cell when an electrical current is applied, dissociating the water molecule to produce OH^- ions and electrons at the anode and producing H^+ ions and electron consumption at the cathode as illustrated schematically below.

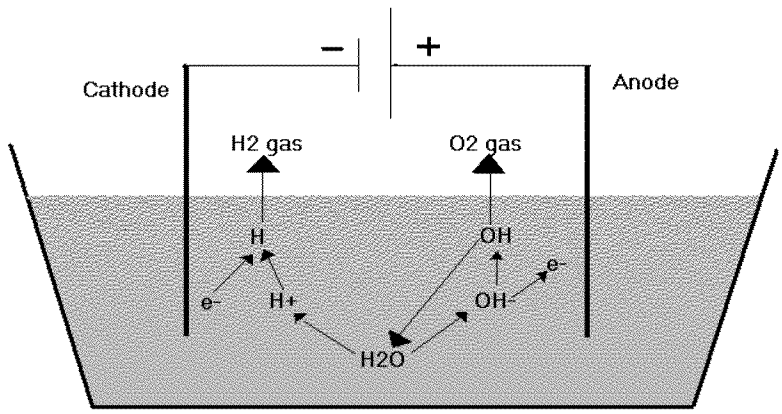

Figure 1- Depiction of Electrolysis in Water

The conventional process for removing heavy metals from wastewater involves precipitation of metal ions via pH adjustment and coagulation / flocculation followed by solids separation. Typically this is accomplished by chemical addition to increase pH thereby forming metal hydroxide precipitates and gravity settling or filtration to separate the solids. Electrochemical treatment is capable of producing an increase in pH without chemical addition, resulting in

metal hydroxide precipitation and formation of hydrogen gas. The apparatus to accomplish this includes three major components: the reactor with electrodes, the power supply, and a solids separation process.

Generally, electrochemical treatment has the advantages of not requiring the addition of chemicals and tends to produce less sludge, with a heavier floc that settles better and is more easily dewatered than other metals removal processes. Power consumption tends to be low under the right conditions, but can be high if water conductivity is low or if electrode scaling occurs. These characteristics make the process potentially highly desirable for application to the Animas River Basin Acid Mine Drainage project due to its remote location and the objective to lower operating costs over the long term.

Potential disadvantages of the process include the need for extensive pilot testing to establish waste-specific operational parameters and limited effectiveness at lower pH values and / or higher metals concentrations.

The process has been tested by others on mining wastewaters and mine drainage water with encouraging results, including the Tyco study conducted by EPA in 1972; electrocoagulation of copper mine wastewater by Rodriguez in 2007; and Electrolysis of Mine Drainage by Arthur in 2010, among others. The Interstate Technology & Regulatory Council provided a review of the technology in August 2010. The results of these studies are mixed, with results being dependent on many factors, making application of the EC process highly situation-specific and indicating the need for extensive pilot-scale investigation to determine feasibility. The studies are included in Appendix D,

3.0 FIRST SITE VISIT

Following the contract award to WWMI the first tasks were discussions with representatives from BLM and the Animas River Stakeholders Group (ARSG), a non-governmental organization (NGO) formed in 1994 with the mission to improve the water quality in the Animas River and its tributaries. Members of the ARSP include interested citizens, land owners, several environmental organizations, mining companies, local government entities and both state and federal regulatory agencies including the BLM and the EPA.

Following discussion which clarified the project priorities and objectives and the schedule of activities, WWMI developed both a Health and Safety Plan and a Pilot Study Sampling Plan and submitted those to the BLM. Once accepted WWMI mobilized a team of four engineers to the American Tunnel Mine site at Gladstone on September 1, 2012. Once at the site samples were taken of the untreated raw water from the American Tunnel adit and delivered to Green Analytical Laboratories (GAL) in Durango, Colorado.

Field tests and water quality sampling were performed during the week of September 3, 2013 through September 7, 2012 with all samples being taken and stored in accordance with EPA water quality sampling methods.

During the first two days of the field sampling and testing work, efforts were made to set up and operate the continuous flow reactor, however difficulties were immediately encountered as observed by the lack of separation of iron in the treated effluent. For two days the pump rates of flow, the voltage and amperage settings and the hydraulic retention times were varied in attempts to identify an optimal operating scheme. However, following two full days of trials it was concluded there was insufficient power reaching the water to achieve electrochemical oxidation and precipitation of the soluble metals in the water and the continuous flow reactor work was suspended.

Following the continuous flow work the WWMI engineers set up and tested the two gallon electrochemical batch reactor. Improved reactions were observed in all batch reactor tests and a range of samples were obtained and taken to GAL for final analytical evaluation.

After the 2012 test, WWMI intended to assess and improve on the power application and then return for additional testing. However, due to BLM scheduled regional water sampling in the Animas River tributaries and the importance not to impact water quality, it was decided that WWMI should wait until after the 2013 spring thaw to return for the second round of sampling and testing.

A detailed description of the field work performed is provided below.

3.1 Description of Equipment Used

WWMI intended to operate two systems during this initial visit to test the EC process in both a batch and continuous flow configurations. The batch system consisted of a 2 gallon batch reactor and an 80-volt, 37-amp DC power supply. The batch reactor contained a series of ¼" diameter aluminum rods serving as electrodes arranged vertically and spaced approximately 1" apart. Power was applied to the electrodes using an AC/DC converter which was connected to mobile generator. The generator chosen for this project was a trailer mounted 45 kW diesel generator. See Figure 2 for a picture of the batch reactor.

The continuous flow system consisted of a 38-gallon reactor, 30 GPM variable speed pump, and a 10 kWatt power supply. This system was skid mounted and then trailer mounted. Additionally, a 1,200 gallon settling tank was used with the flow through system. See Figure 3 for a picture of the system.

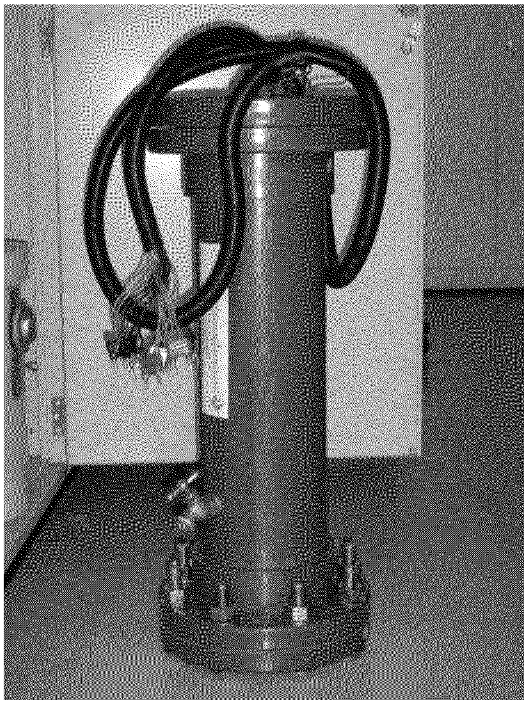

Figure 2 – EC Batch Reactor

Figure 3 – 30 GPM Flow-through Reactor Skid

3.2 EC Testing Procedures

3.2.1 Continuous Flow Test Procedure

For the continuous, flow-through test a variable speed pump was used to transfer water from the adit drainage stream through the electrochemical reactor and into a clarifier tank. Precipitated solids would settle in the clarifier and effluent water would overflow back into the adit stream at a point downstream of the raw water intake location. Accumulated sludge would be drained from the clarifier as needed to maintain the proper operation of the clarifier. Drained sludge would be discharged to the adit stream at a point downstream of the raw water intake location.

The continuous test was intended to run 24 hours per day for a total of 5 days. At the conclusion of the field work, all equipment was flushed with raw stream water and drained back to the adit drainage stream before transport from the site.

3.2.2 Batch Test Procedure

Batch tests were conducted in a separate reactor at various retention times and various power levels to determine the effect of varying retention times and charge densities in the reactor. For each batch test, the reactor was filled with raw water from the adit drainage stream, the reactor was sealed and the test run for a pre-determined time before the power was shut down. At the conclusion of each batch test, samples were drawn directly from the reactor and tested for settleability, physical and chemical characteristics. Remaining residuals in the reactor were flushed back into the stream using raw water. The reactor was properly decontaminated prior to the next batch test. All decontamination residuals were contained and properly disposed of to the sanitary sewer.

After each batch test, one sample for total suspended solids (TSS) was drawn directly from the reactor. Additionally, two one-liter jars were filled with treated water directly from the reactor and the pH and conductivity were measured prior to allowing the jars to stand, covered and undisturbed for fifteen minutes. After this quiescent period, filtered and

unfiltered samples were drawn using a disposable syringe and 45 micron filter. All samples were packed on ice, preserved as necessary, and delivered to GAL in Durango, Colorado for analysis.

The samples were analyzed for general chemistry components including alkalinity, chloride, sulfate, and TSS. Other samples were analyzed for total and dissolved constituents including aluminum, iron, calcium, magnesium, potassium, sodium, cadmium, copper, lead, manganese, zinc, and mercury.

3.3 Testing Results and Observations

Although the continuous testing program was unsuccessful, eleven batch tests were conducted at various retention times and power settings and samples of the treated water from each batch test, along with one raw water sample were analyzed by Green Analytical Laboratory in Durango, Colorado. The results of all analyses are presented in Table 1 and the laboratory reports and chain-of-custody documentation are provided in Appendix C.

Results of the September 2012 testing are summarized as follows:

- The 2012 raw water quality aligned with the reported 2009 – 2011 raw water quality.
- Observed floc formation and settling during the 15- minute quiescent period, leaving a clear supernatant following each batch test.
- TSS was reduced by as much as 92%.
- pH decreased slightly in all but one test.
- Conductivity was reduced slightly in each test.
- Dissolved aluminum (from the electrodes) increased directly with an increase in hydraulic retention time.
- Dissolved iron was reduced inversely with an increase in hydraulic retention time by as much as 95% of the initial value.
- Sodium was reduced to "non-detect" levels at hydraulic retention times above five minutes.
- Both dissolved and recoverable zinc was reduced between 15% and 60%.

- Both dissolved and recoverable cadmium was reduced to “non-detect”.
- Both dissolved and recoverable copper increased with an increase in retention time.
- Both dissolved and recoverable lead increased with an increase in retention time.
- Both magnesium and manganese were unchanged.
- Observed oxide deposition on the cathodes.

TABLE 1

Sample Number	ECD-R	ECD-1	ECD -2	ECD -3	ECD -4	ECD -5	ECD -6	ECD -7	ECD-8	ECD-9	ECD -10*	ECD-11**
Test Parameters												
HRT - REACTOR (MIN)		6	3	1.5	6	3	9	6	9	15	9	9
HRT - SETTLING (MIN)		15	15	15	15	15	15	15	15	15	15	15
VOLTS - INITIAL (DC)		27	37	44	50	50	50	63	62	60	74	37 - 57
VOLTS - FINAL (DC)		23	40	48	50	50	50	40	26	19	40	40
AMPS - INITIAL (DC)		37	37	37	22	17.5	17.3	37	37	37	37	37
AMPS - FINAL (DC)		37	37	37	31	20	25	37	37	37	37	37
pH -FINAL		5.25	4.7	4.86	4.58	4.51	4.24	4.32	4.12	4.09	4.7	4.2
CONDUCTIVITY		2200	2230	2310	2215	2304	2248	2225	2190	2035		
General Chemistry (mg/l)												
ALK, BICARBONATE		ND	ND	ND	ND	ND	ND	ND	ND	ND	10	<10
ALK, CARBONATE		ND	ND	ND	ND	ND	ND	ND	ND	ND	<10	<10
ALK HYDROXIDE		ND	ND	ND	ND	ND	ND	ND	ND	ND	<10	<10
ALK , TOTAL		ND	ND	ND	ND	ND	ND	ND	ND	ND	<10	<10
CHLORIDE		20	ND	ND	ND	ND	ND	ND	ND	ND	<10	<10
SULFATE		1300	1600	1700	1650	1750	1700	1750	1650	1600	1460	1520
TSS		1180	480	200	760	90	480	450	640	950	1440	1320
Total Recoverable Metals by ICP (mg/l)												
ALUMINUM	4.7	11.2	4.48	7.69	10.3	13.9	29	39.8	55.6	54.2	5.07	15.6
IRON	142	96.9	96.8	122	73.4	113	58	75.3	47.8	47	19.1	30
Dissolved Metals by ICP (mg/l)												
ALUMINUM	4.6	ND	1.48	3.01	9.17	11.5	28.1	35.1	45.4	74.5	3.09	16.1
CALCIUM		380	427	442	432	444	418	393	375	326	407	425
IRON	136	95.9	95	114	70.3	103	55.7	65.1	37.7	7.86	17	31.8
MAGNESIUM		30.3	31	31.7	31.9	32.7	32.3	30.9	31.2	30.7	28	29
POTASSIUM		ND	ND	ND	ND	ND	ND	ND	ND	ND	<10	<10
SODIUM		29.1	16.1	14.6	15.5	11.4	ND	ND	ND	ND	17.5	<10
Potentially Dissolved Metals by ICP (mg/l)												
ZINC	21.3	9.52	17	19.8	19	19.8	19.9	20.1	20.1	19.8		

Total Recoverable Metals by ICPMS (mg/l)												
CADMIUM	0.0021	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
COPPER	0.01	0.211	4.76	5.37	22.8	8.28	14.3	10.3	10	10.4	22.6	11.9
LEAD	0.0029	0.0609	0.123	0.116	0.854	0.275	0.771	0.826	0.884	1.09	0.926	0.914
MANGANESE	49	44.4	46	46.1	45.9	46.9	47.3	48	45.3	45.1	43.3	44.9
ZINC	20.8	8.95	15.3	17.6	16.3	17	17.1	17	16.6	16.6	12.6	14.4
Dissolved Metals by ICPMS (mg/l)												
CADMIUM	0.002	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
COPPER	0.02	ND	4.61	4.8	21.5	8.44	13.4	9.54	9.98	9.7	20.5	11.1
LEAD	0.0013	ND	0.106	0.093	0.849	0.26	0.749	0.71	0.885	1.06	0.897	0.924
MANGANESE	46.5	44.3	46.6	46.9	46.3	46.9	45.6	47.2	46.4	47	44.8	45.6
ZINC	19.3	8.51	14.2	15.6	15.3	15.8	16.2	16.3	16	16	14.4	17.2
Total Mercury by CVAA (mg/l)												
MERCURY		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dissolved Mercury by CVAA (mg/l)												
MERCURY		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

4.0 SECOND SITE VISIT

After the second site visit schedule was confirmed with the BLM representatives, two WWMI engineers returned to Colorado to perform further testing and analysis in August 2013. The WWMI engineers arrived at the site on August 4, 2013 and set up the continuous flow system and readied the site for further testing. Field work was then performed during August 5, 2013 through August 9, 2013.

4.1 Description of Equipment Used

During the period between the work in September 2012 and returning to the site WWMI engineers analyzed the observed and recorded data relating to the difficulties encountered with the continuous flow reactor and the modifications made to the treatment system. The control system was rewired with larger wires, the power converter was increased in size from 10,000 Watts to 15,000 Watts and the power generator was increased from 25 KVA to 45 KVA so that the power delivered to the reactor during the 2013 trials was approximately four times greater than in 2012.

4.2 EC Testing Procedures

Similar to the circumstances observed in 2012, there were no observed electrochemical reactions occurring within the continuous flow reactor at the higher power applications. What was observed was the applied current at 60 amps at the start of the test trials would immediately drop to 0 amps within a few seconds. This phenomenon was observed repeatedly and the only thing that seemed to occur was the heating of the water.

After two days of working with the larger continuous flow system the WWMI engineers decided to fabricate and test a smaller continuous flow reactor to see if by significantly increasing the current density applied to the water, effective treatment could be achieved. This smaller reactor was constructed as a 1.36 gallon unit with ¼” diameter aluminum electrodes spaced approximately 7/8” apart. The electrodes were wired directly to the

generator to provide alternating current. The flow rate used with this reactor was varied from 1 GPM to 0.4 GPM providing hydraulic retention time s of between 1 and 4 minutes. On August 8, 2013 the engineers were successful in usi ng the smaller continuous flow reactor operating at several hydraulic retention times. Fo r each test, water was pumped through the reactor with power applied during the entire time a t the flow rate indicated to produce the two retention times, then one liter jars were filled di rectly from the reactor discharge and allowed to stand undisturbed for 15 minutes. After this quiescent period, samples were collected using a disposable syringe and 45 micron filter. All samples were packed on ice, preserved as necessary, and delivered to GAL for analysis.

The samples were analyzed for general chemistry com ponents including alkalinity, chloride, conductivity, pH, phosphate, and sulfate. Other samples were analyzed for total and dissolved constituents including aluminum, iron, silica, sili con, calcium, magnesium, potassium, sodium, cadmium, copper, lead, manganese, zinc, and mercury.

On August 9, 2013 WWMI engineers demobilized from the site.

During the final continuous flow testing using the smaller reactor the voltage and amperage measured 90 volts and 66 amps being read directly f rom the gages on the mobile power unit. These power rates during the continuous flow testin g period resulted in power being applied at the rate of 5,940 watts per an average of 2 gallons, or 3kW per gallon of water treated. At a conventional power purchase rate of $0.08 per kW-hr the price of electricity for treatment would be 3 kW-hr to treat 60 gallons or $0.24 per h our to treat a 1 gallon per minute flow stream. Per day the cost to purchase electricity would be $5.76 per 1 gallon per minute rate of flow. Thus at an average rate of flow as reported in the July 2012 MWH report of 106 gallons per minute the daily power cost would be $610.56 at an annual power purchase cost would be $222,854.40.

4.3 Testing Results and Observations

The results of all analyses are presented in Table 2 and the laboratory reports and chain-of-custody documentation are provided in Appendix C.

Results of the continuous flow tests during August 2013 are summarized as follows:

- The 2013 raw water quality aligned with the 2012 raw water quality.
- Observed floc formation and settling during the 15- minute quiescent period, leaving a clear supernatant following each test.
- Dissolved aluminum (from the electrodes) was increa sed by a factor of 10 due to the greater application of power.
- Dissolved iron was reduced inversely with an increase in hydraulic retention time
- Sodium was essentially unchanged.
- Both dissolved and recoverable cadmium was reduced by approximately 30%.
- Both dissolved and recoverable copper was reduced by approximately 50%.
- Both dissolved and recoverable lead was reduced by at least 50%.
- Both magnesium and manganese were unchanged.
- pH and conductivity were reduced in each test.
- Both dissolved and recoverable zinc was unchanged i n the 2-minute test and reduced by approximately 20% in the 5-minute test.
- Oxide deposition on the cathodes was again observed.

TABLE 2

Sample	Raw -1	Raw	2-Min	5-Min #1	5-Min #2
Test Parameters					
HRT - REACTOR (MIN)			2	5	5
HRT - SETTLING (MIN)					
VOLTS - INITIAL (DC)					
VOLTS - FINAL (DC)					
AMPS - INITIAL (DC)			66	66	66
AMPS - FINAL (DC)			66	66	66
pH -FINAL	5.88	5.5	4.79	4.97	5.00
CONDUCTIVITY	2380	2390	2270	1980	1990
General Chemistry (mg/l)					
ALK, BICARBONATE	10	<10.0	<10.0	<10.0	<10.0
ALK, CARBONATE	<10.0	<10.0	<10.0	<10.0	<10.0
ALK HYDROXIDE	<10.0	<10.0	<10.0	<10.0	<10.0
ALK , TOTAL	<10.0	<10.0	<10.0	<10.0	<10.0

CHLORIDE	<10.0	<10.0	<10.0	<10.0	<10.0
SULFATE	1660	1650	1550	1340	1340
TDS	2460	2480	2280	2120	2080
Total Recoverable Metals by ICP (mg/l)					
ALUMINUM	5.19	5.2	66	201	148
IRON	168	158	214	155	134
Silica (Si02)	27.7	1650	42.1	32.7	28.6
Silicon	13	2480	19.7	15.3	13.4
Dissolved Metals by ICP (mg/l)					
ALUMINUM	3.5	2.62	6.52	2.44	2.06
CALCIUM	466	446	416	362	365
IRON	168	144	127	109	104
MAGNESIUM	32.4	32.1	31.2	27.8	27.2
POTASSIUM	<20	1.28	<1.00	1.58	1.05
Silica (Si02)	<21.4	36	32.8	23.5	22.8
Silicon	<10	16.8	15.4	11	10.7
SODIUM	<20	8.39	8.2	8.49	8.61
Potentially Dissolved Metals by ICP (mg/l)					
ZINC					
Total Recoverable Metals by ICPMS (mg/l)					
CADMIUM	0.01	0.0025	0.0021	0.0018	0.0016
COPPER	0.1	0.0106	0.1	0.041	0.0245
LEAD	0.05	<0.0050	0.0419	0.026	0.0122
MANGANESE	48.5	46.2	46.5	39.5	39.2
ZINC	19.6	27.5	30.9	24.6	21
Dissolved Metals by ICPMS (mg/l)					
CADMIUM	<0.002	0.0027	0.0027	0.0022	0.0017
COPPER	<0.002	0.0108	0.0127	0.0056	0.0039
LEAD	<0.01	<0.0050	0.0071	0.0072	<0.0050
MANGANESE	48.8	50.2	42.8	40.9	38.7
ZINC	19.6	16.9	15.5	12.4	11.4
Total Mercury by CVAA (mg/l)					
MERCURY	<0.0010	<0.0002	<0.0002	<0.0002	<0.0002
Dissolved Mercury by CVAA (mg/l)					
MERCURY	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002

5.0 DISCUSSION OF RESULTS

The effectiveness of the EC process for removal of metals is based on hydroxide production via electrolysis and the resulting pH increase and precipitation of insoluble metal hydroxides. The results of this pilot testing were generally encouraging. As shown in Figure 4 of test #9 before and after settling, it appears that hydroxide ions were produced by electrolysis and ferrous iron was successfully oxidized to ferric iron, resulting in production and precipitation of ferric hydroxide.

Figure 4 – Test #9 Before and After Settling

However, insufficient hydroxide was created to provide the desired increase in pH. It is possible that ferric iron production was limited by back-reduction to ferrous iron at the cathode due to the low pH.

Based on the observed positive correlation between hydraulic retention time and iron reduction as well as the visual observation of orange floc formation, the process was effective at reducing the concentrations of dissolved iron and producing a settleable floc. Longer retention times might have allowed for complete removal of iron, as well as further reductions in other constituents either by co-precipitation with the iron hydroxide floc or by the increase in pH that should result after removal of all oxidized iron.

Finally, oxide deposition on the cathodes could have caused an increase in electrical resistance, which would have resulted in decreased current at constant voltage in accordance

with Ohm's law. This could be overcome by the use of AC power or by employing automated polarity reversing in a DC power supply.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The demonstrated *Rigby EC Process* treatment system showed some limited promise for being capable of treating the mine adit drainage to an acceptable level for introduction into the Animas River basin. However, to improve effectiveness it is believed that it is necessary to adjust the pH of the raw water prior to electrochemical treatment. It is also believed that a longer hydraulic retention in the reactor would be beneficial in removing greater percentages of heavy metals from the water. The use of chemical pH adjustment to near neutral prior to the electrochemical treatment as well as longer hydraulic retention times should produce desirable results. However, because of the difficulties encountered with the low pH and high conductivity water there was insufficient data collected at a sufficiently wide range of values to reliably predict success at this time.

Hypothetically, however, extrapolating the data gathered during the small unit continuous flow sampling program, the following broad estimate conclusions can be drawn.

<u>Process Flow Schematic:</u> Raw water from adit would flow directly into a preliminary pH neutralization tank from where it would be pumped through an electrochemical treatment reactor. From the reactor the water would flow through a gravity clarifier and thereafter discharge to the waters of Cement Creek. The clarifier underflow would be pumped to a sludge tank for accumulation prior to being pumped through a plate and frame filter.

<u>Capital Cost Estimate:</u> For a 200 gallon per minute treatment reactor the fabrication cost would be approximately $500,000. Including the pH neutralization tank, the clarifier, the sludge press, the chemical feed systems and a stand by power generator along with a small control building and site improvements an order of magnitude capital budget cost would be $1,700,000.00.

<u>Annual Operating Cost Estimate:</u> As noted in the text the cost of power, whether line power or produced power would be approximately $223,000.00 per year. Adding the cost of one and a half operators at a $75,000.00 per year each plus the cost of neutralizing pH chemicals,

dewatered sludge disposal and routine maintenance and replacement an order of magnitude annual operating budget would be $700,000.00.

Potential for Economies of Scale: The question was posed whether it would be more cost effective to implement a program with a treatment system at each individual mine adit or whether it would be more cost effective to combine two or more mine discharges into a single treatment system. The obvious answer is it depends on the distance between the mine adits. Other than the mine adit at the primary treatment site, each separate adit would require a separate pump station with a power supply and site improvements plus the interconnecting pipeline. Each pump station should cost in the order of magnitude of $250,000.00 plus the cost of the pipeline which could range between $60.00 and $100.00 per foot to install.

In addition, since the treatment systems are essentially based on hydraulic factors an increase in flow would result in probably and 80% increase in capital costs and operating costs not including labor. However, the higher capital and operating costs of the centralized treatment scenario should be compared to the higher costs for additional operators plus travel costs between sites if decentralized treatment is considered.

Operator Training: Most states require water and wastewater system operators to be trained and certified to be allowed to work at public utilities. Most non-public facilities such as wet industries often do not insist on the same level of training. Within each state and nationally there are many well-conceived and developed programs for operator training and operators can become certified separately in water, wastewater and industrial wastewater disciplines. In addition, every operator training program offers a range of levels of competency from a low assistant operator to an executive manager and program administrator level. In the case of the electrochemical program required for the treatment of mine drainage water an operator trained in industrial wastewater with mid-level certification would be sufficient.

APPENDIX A

Statement of Work

Electrochemical Water Treatment Pilot Test

Cement Creek Drainage
San Juan County, Colorado

May 18, 2012

Introduction

The Animas River Stakeholders Group (ARSG) is an organization formed in 1994 with participants that include mining companies, citizens, environmental organizations, land owners, local governmental entities, and state and federal regulatory and land management agencies. This organization has a mission to improve the quality of all streams in San Juan County, Colorado that are tributary to the Animas River. The Bureau of Land Management (BLM) is a participant in the ARSG, and will serve as the contracting agency for the scope of work described in this Request for Proposal (RFP).

The ARSG is currently evaluating alternatives to improve water quality in the Upper Cement Creek drainage in San Juan County. There are four significant mine adits and a few smaller ones that are currently draining low pH mine water heavily laden with dissolved metals into Upper Cement Creek. As part of the effort to identify alternatives to address these discharges, the ARSG has elected to pilot test the electrochemical treatment of water. This treatment methodology exposes the contaminated water to an electric field to initiate the precipitation of the contaminants of concern.

The ARSG is currently seeking companies experienced in the treatment of mine waters with electrochemical processes, and experienced in the design and manufactures of full-scale electrochemical water treatment systems.

Statement of Work

1) Conduct pilot test of electrochemical coagulation to treat mining impacted waters near Gladstone, north of Silverton, Colorado. The full flow of the American Tunnel is available for the test. Target date for the test is August or September 2012 (to be negotiated), and exact dates will need to avoid interference with basin-wide water characterization also scheduled for the Fall.

2) Demonstrate that the electrochemical process is capable of meeting treatment goals by extrapolating the test on the American Tunnel to the other adits. Adit flows and chemistry are in Appendix A. Treatment goals are provided in Appendix B.

3) Characterize and identify all input reagents, power consumption and waste streams generated by this treatment process.

4) Gather data required to scale-up data collected in pilot test to design a full-scale system.

5) Recommend whether a full scale system would treat each of the adits separately or commingle into a single stream.

6) Estimate full-scale capital cost
7) Estimate full-scale annual operations and maintenance costs
8) Provide estimated characterization for wastes produced by a full-scale system.
9) Describe any cost savings (capitol or operational) if treatment goals were adjusted to allow discharge of more contaminants
10) Recommend the number of operators required to operate a full-scale system and the level of training required for these operators.

11) Remove all test facilities from the site, and leave the site in similar condition as on arrival.

Deliverables

Prior to the pilot test, provide a Health and Safety Plan.

At the completion of the pilot test, provide a DRAFT written report that contains the following:

4. A table showing analysis of the raw water and treated water as collected a part of this pilot test.
5. Treatment goals used to design the pilot test
6. Description of the pilot test performed including a process flow diagram
7. Description of any difficulties encountered during the pilot test, and how they impact the ability to use the pilot test to estimate full-scale implementation
8. Raw test data provided in a report appendix and a summary of treatment data in the report text.
9. Statement that data was collected to provide the bidder with the data required to scale up the pilot test system into a full-scale system.
10. Recommendation to treat each of the adits separately or to commingle into a single stream.
11. Recommendation for a full-scale system.
12. Estimate of capital cost for a full-scale system
13. Estimate of annual operations and maintenance cost for a full-scale system.
14. Recommend the number of operators required to operate a full-scale system and the level of training required for these operators.

Provide a FINAL written report incorporating comments from the ARSG.

Proposal Format

The following shall be provided in the bidder's proposal:

1. Details related to the Bidder including year of incorporation under the current business name, number of years providing electrochemical water treatment systems, number of employees, amount of annual sales, location of main administrative office.
2. Resume of the lead technical person managing the pilot test work, and project resume for the company.

3. Provide 3 references for past performance using the attached Past Performance Questionnaire.
4. Provide details of the proposed pilot test including the flow rate and duration proposed and the rationale for this determination.
5. Provide a detailed breakdown of costs for the pilot test, including office time, field time, expenses, equipment rental, mob/demob, etc.
6. Responses to the following questions:
    a. How many pilot tests have you performed with your electrochemical technology, what was the application (industrial/mining), what was the test flow rate, treatment goals, where was it located, and is test data available?
    b. How may full-scale systems have you supplied with your electrochemical technology, what was the application (industrial/mining), what is the design flow rate, regulatory driver for treatment, treatment goals, how long has it been operating where was it located, and can we contact the owner?
    c. List reagents and chemicals used in the test.
    d. Describe analytical tests that are needed and the frequency of sampling. Provide a table showing the number, type and costs of analytical tests required for the entire pilot test.
    e. Please confirm that the pilot test effort will include prediction of full-scale capital cost and annual operating cost.
    f. At full-scale conditions, please estimate the volume of sludge produced and the characteristics of that sludge.
    g. Please describe dewatering of the sludge produced and how that might be accomplished at Gladstone.
    h. Does your system require the influent water be adjusted to near neutral pH before treatment?
    i. Is there any level of conductivity required for your system to be effective?
    j. Are there temperature limitations on the influent flow?
    k. Are there variances in metals concentrations that cannot be addressed with the treatment system?
    l. Are there limitations on suspended solids, and
    m. Are there requirements for the pretreatment of iron?
    n. Are there any known process limitations?
    o. How is corrosion/oxidation of the electrodes managed, material selection or replacement?
    p. Are there metals found in mine drainage that electrocoagulation is not effective in removing?
    q. What are the power requirements for a full-scale system?
    r. Is your treatment system available in 100 gpm modular units so the system can be expanded or reduced if needed?

s. For a full-scale system, what would the duration of a warranty be, and what would be included in a warranty?

Selection Criteria

Criteria used to evaluate proposals will include the following:

1. Past Performance (20%)

   Experience with pilot test and operational systems. Should the BLM elect to contact references; the bidder will be evaluated on the quality of service, timeliness of performance and overall customer satisfaction provided.

2. Technical (60%)

   This element will include:

   The project approach described for the conduct of the pilot test
   The limitations of the technology as per questions f) through r) above
   The technical strength of the bidding organization and its technical team

3. Cost of proposed pilot test (20%)

Site Details

The site is adjacent to a graveled county road and has a moderately level space of less than one half acre. It is approximately 350 ft. from the adit drainage at the American Tunnel. The bidder will be required to provide pumps and piping capable of delivering water from the American Tunnel and returning treated water to the same channel. The bidder will be responsible for providing site power via portable generator, and any required site security fencing and site lighting if needed. The bidder will have access to the site 7 days a week and 24 hours per day during the period of performance in the contract. At the end of the test, the bidder will remove all test equipment and will leave the site in similar condition as found.

Water Quality

Water quality and flow rates for each of the following adits are included in Appendix A.

1. American Tunnel
2. Red and Bonita Mine
3. Gold King No. 7
4. Mogul
5. Gold Point
6. Pride of Bonita

Linda Neslon (BLM Southwest District, Montrose) will be the COR for this project.
Cathleen (Kay) Zillich (BLM Tres Rios Field Office, Durango) is the PI for technical questions.

APPENDIX B

Electrochemical Pilot Study Sampling Plan

Preface

An on-site pilot test will be performed with an electrochemical water treatment pilot unit to demonstrate the removal of heavy metals and total suspended solids from mine adit drainage water in the Upper Cement Creek area of the Animas River watershed in San Juan County, Colorado. Requirements for the work were outlined in the Statement of Work – Electrochemical Water Treatment Pilot Test, dated May 18, 2012 and issued by the Bureau of Land Management, Abandoned Mine Program, Durango, Colorado.

The Statement of Work included a description of the goals of the test, deliverables required, raw water quality data, and Water Quality Treatment Goals for an eventual full-scale system to treat all mine adit drainage in the area. The pilot test work will be performed on the American Tunnel adit drainage under the U.S. Bureau of Land Management Requisition Number 0040043010, Order Number L12PX01360 issued to Waste Water Management, Inc. (WWMI) on July 23, 2012.

Intent

The American Tunnel adit drainage water will be treated using an electrochemical water treatment process to determine:

1. The effectiveness of electrochemical treatment for the precipitation of particulate and dissolved aluminum, iron, cadmium, copper, lead, manganese, zinc, and mercury.

2. The optimal charge density and retention time in the electrochemical reactor.

3. Solids settling characteristics and pH and total suspended solids of clarified effluent discharged back to the stream.

4. The volume of sludge byproduct expected to be generated, characterization of the sludge, evaluation of dewatering methods, and disposal options.

5. Other necessary information to provide a capital and operating cost estimate for a future full-scale unit.

Testing Approach - General

The general approach for the pilot test will be to run several batch tests as well as a multi-day continuous flow-through test of the electrochemical treatment process. The batch tests will be used to determine the hydraulic retention time and power level in the reactor that will be used to scale up the process. The purpose of the continuous test is to demonstrate the performance of the electrochemical process in a continuous flow-through configuration and to produce sludge solids for dewatering testing and characterization. WWMI personnel will be on site at all times that the equipment is in operation. At the conclusion of testing, all equipment will be cleaned and drained, all debris and equipment collected, and the site will

be returned to the condition in which it was found upon arrival. All activities during the pilot test will be recorded in the field log.

Physical characteristics such as temperature, pH, total suspended solids, and conductivity as well as chemical characteristics (i.e. metals concentrations) will be determined for raw and treated water in both the continuous and batch tests. At the conclusion of the continuous test, a sample of settled sludge will be shipped to an off-site testing facility to determine its dewatering characteristics. Dewatered samples will be analyzed using the Toxicity Characteristic Leaching Procedure.

Continuous Test Procedure

For the continuous, flow-through test a pump will transfer water from the adit drainage stream into a holding tank, another pump will transfer water from the holding tank through the electrochemical reactor and into a clarifier tank. Precipitated solids will settle in the clarifier and effluent water will overflow back into the adit stream at a point downstream of the raw water intake location. Accumulated sludge will be drained from the clarifier as needed to maintain the proper operation of the clarifier. Drained sludge will be discharged to the adit stream at a point downstream of the raw water intake location.

The raw water pump will operate at a rate sufficient to maintain a minimum water level in the holding tank. The holding tank will overflow back into the stream at a point downstream of the raw water intake location to avoid disturbance of the incoming raw water stream.

It is assumed that the adit drainage flows constantly at a rate of at least 20 gallons per minute, which is the flow rate planned for the continuous test. If the stream is not flowing or flows at a rate lower than the test flow rate, the test flow rate will be adjusted as necessary and the information recorded in the pilot test log.

The continuous test will run 24 hours per day for a total of 5 days. At the conclusion of the continuous test, all equipment will be flushed with raw stream water and drained back to the adit drainage stream before transport from the site.

Batch Test Procedure

Batch tests will be conducted in a separate reactor at various retention times and various power levels to determine the effect of varying retention times and charge densities in the reactor. For each batch test, the reactor will be filled with raw water from the adit drainage stream, the reactor will be sealed and the test run for a pre-determined time before the power is shut down. At the conclusion of each batch test, samples will be drawn directly from the reactor and tested for settleability, physical and chemical characteristics. Remaining residuals in the reactor will be flushed back into the stream using raw water. The reactor will be properly decontaminated prior to the next batch test. All decontamination residuals will be contained and properly disposed of to the sanitary sewer.

Sampling Methodology

Water samples will be collected and analyzed to determine the physical and chemical characteristics of the raw, untreated water from the adit drainage stream as well as the treated effluent water from both the continuous and batch tests. Sludge samples will be collected to determine its dewaterability by several mechanical methods and the dewatered

sludge will be analyzed to determine options for disposal. All samples will be collected, handled, shipped, and analyzed in accordance with applicable USEPA methods. Sample analyses will be performed by Green Analytical Laboratories (Durango, Colorado). Sludge dewaterability testing will be performed by Andritz Separation, Inc. (Arlington, Texas).

Sample Locations

Raw water samples will be collected from the surface of the raw water holding tank.

Treated effluent water from the continuous test will be collected from the surface of the clarifier at the effluent overflow fitting on the tank.

Treated effluent water from the batch tests will be collected by drawing treated water from a sample tap on the batch reactor into a collection container, such as a glass beaker. A portion of the collected water will be poured into a separate container to test settleability. The remaining portion of the water in the beaker will be set aside to allow solids to settle for 30 minutes. Sample bottles will be filled by carefully decanting the supernatant from the beaker directly into each sample bottle.

One field blank sample will be collected for each of the three sampling locations following identical sample collection methods and using bottled, deionized water provided by the laboratory with the sample bottles.

Settled sludge from the continuous test will be collected directly from the drain connection on the bottom of the clarifier tank. Two 2.5-gallon sample containers will be filled for shipment to the Andritz Separation facility.

Sampling Frequency

The raw water has already been characterized by previous sampling efforts with the data included in the Statement of Work. One raw water sample will be taken at the initiation of testing to compare to this data. Analyses for mercury, which had not been previously reported, will be added to the analyte list to comply with the Water Quality Treatment Goals.

Treated effluent water will be sampled one time during the continuous flow-through test. Treated effluent water will also be sampled at the conclusion of each of the batch tests.

Settled sludge will be sampled once for off-site testing of dewaterability and subsequent analysis of the dewatered sludge.

Sample Collection

All samples will be grab samples. Sample containers and preservative chemicals will be provided by the laboratory that will conduct the analyses. Sample collection devices will include glassware as necessary to collect water from tanks and transfer into sample bottles. All glassware will be properly decontaminated prior to each sample collection event.

Sample collection from tanks will be conducted by manually dipping a glass collection container, such as a beaker or graduated cylinder, partially below the water surface to fill the container. The sample bottles will be filled by pouring the sample from the collection

container into the sample bottle. Preservative chemicals will be added according to laboratory instructions.

Each sample bottle will be labeled at the time of collection with all information provided on the adhesive label affixed to the bottle with all information transferred to the chain-of-custody document.

Sample Handling and Shipping

All samples will be analyzed on site for various physical parameters including temperature, pH, and conductivity. Measurements will be made using handheld instruments, properly calibrated according to the manufacturer's instructions.

All samples will be packaged, stored, and shipped under proper chain-of-custody documentation, observing applicable holding times, and according to laboratory instructions. Samples being analyzed by Green Analytical will be hand delivered to their Durango facility at the conclusion of testing. The sludge dewaterability sample will be shipped via FedEx or other overnight carrier for next business day delivery to the Andritz facility in Arlington, Texas.

Sample Analyses

All eleven (11) water samples and all field and trip blanks will be analyzed for total suspended solids (TSS) and metals. The TSS analysis will be conducted according to EPA Method 160.2 with a method detection limit of 4 mg/L. Water samples analyzed for metals will use the methods shown in the table below with their associated method detection limits.

EPA Method	**Analyte**	**MDL**	**Water Quality Treatment Goals**		**Units**
			Daily Max	**30-day Avg**	
Total Recoverable Metals by ICP in Water					
6010B	Aluminum	0.00640	N/A	N/A	mg/L
6010B	Iron	0.00430	N/A	N/A	mg/L
Dissolved Metals by ICP in Water					
200.7	Aluminum	0.00640	N/A	N/A	mg/L
200.7	Iron	0.00430	N/A	N/A	mg/L
Total Recoverable Metals by ICPMS in Water					
6020A	Cadmium	0.0000212	0.10	0.05	mg/L
6020A	Copper	0.0000306	0.30	0.15	mg/L
6020A	Lead	0.0000210	0.6	0.3	mg/L
6020A	Manganese	0.0000458	N/A	N/A	mg/L
6020A	Zinc	0.000103	1.5	0.75	mg/L
Dissolved Metals by ICPMS in Water					
200.8	Cadmium	0.0212	0.10	0.05	mg/L
200.8	Copper	0.0306	0.30	0.15	mg/L
200.8	Lead	0.0210	0.6	0.3	mg/L
200.8	Manganese	0.0458	N/A	N/A	mg/L
200.8	Zinc	0.1030	1.5	0.75	mg/L

Total Mercury by CVAA in Water					
245.1	Mercury	0.0000125	0.002	0.001	mg/L
Dissolved Mercury by CVAA in Water					
245.1	Mercury	0.0000125	0.002	0.001	mg/L

Notes:
MDL = Method Detection Limit
ICP = Inductively Coupled Plasma
ICPMS = Inductively Coupled Plasma - Mass Spectrometry
CVAA = Cold Vapor Atomic Absorption

Water samples to be analyzed for dissolved metals will be filtered by the laboratory. No filtering of samples will be performed in the field.

One (1) sample of the dewatered sludge will be collected and packaged at the Andritz Separation laboratory and shipped under proper chain-of-custody to Green Analytical for TCLP analysis for metals constituents according to EPA Method 1311.

APPENDIX C

Analytical Test Results from Green Analytical Laboratories

C.1 – Results Dated 20 September 2012

C.2 – Results Dated 26 September 2012

C.3 – Results Dated 16 August 2013

C.4 – Results Dated 21 August 2013

APPENDIX D

Treatment of Acid Mine Drainage – Reports by Others